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Title
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Permalink
https://escholarship.org/uc/item/6013c49g

Journal
Building and Environment, 167

ISSN
0360-1323

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Publication Date
2020

DOI
10.1016/j.buildenv.2019.106462

Peer reviewed

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Interactions and Comprehensive Effect of Indoor Environmental Quality Factors on Occupant Satisfaction

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Abstract

In this study, eight subjects were exposed in a simulated office to 31 combinations of indoor environmental conditions, assigned by orthogonal design and uniform design. Conditions comprised variations of Predicted Mean Vote (PMV), illuminance, sound pressure and CO_2 concentration (independent of a consistent ventilation rate) as indicators of thermal, lighting, acoustic and indoor air quality. Participant satisfaction with each of the four factors and with overall environmental conditions were measured with a questionnaire. Multiple interactions were detected with a partial correlation analysis and regression analysis. Results showed an adjusted effect of illuminance on perceived acoustic environment, a significant effect of the thermal environment on indoor air quality satisfaction, and a slight effect of sound pressure on indoor air quality satisfaction. Linear and geometric mean regression models were investigated for predicting overall satisfaction from the factor satisfaction scores. For the linear model, it was determined that multicollinearity among factor satisfaction levels may result in non-significant and biased estimated coefficients. The geometric mean regression model provides better prediction accuracy than the linear regression model with fewer coefficients, and accounts for the finding that the lowest satisfaction level with any environmental factor appears to drive overall satisfaction.

Keywords: interaction; perceived indoor air quality; thermal comfort; carbon dioxide; office environment; lighting

1. Introduction

Many previous studies have provided overwhelming evidence demonstrating that indoor environmental quality (IEQ) has a significant impact on occupant health, comfort and productivity [1,2]. The significance of (IEQ) in the assessment of building performance has been highlighted in many building standards[3–5].

1.1 Interactions between individual environmental factors

Indoor environmental quality is generally considered to include four principal factors: thermal environment, sound, light and indoor air quality (IAQ) [6]. While most studies in this area have sought to better understand the independent import of each factor, some studies have shown that a change in one factor may impact on the sensation of other factors. There are two different kinds of interactions: objective and subjective. Objective interaction occurs when a physical element or a characteristic that is associated with one environmental factor impacts some physical parameter that is associated with another factor. An example of this type is that temperature and humidity (thermal environmental indicators) impact emission rates of some chemical air contaminants from building materials [6], causing a direct physical impact on IAQ conditions. A subjective interaction occurs when the magnitude of one physical element impacts human perception or satisfaction with a separate element, even when the physical indicators of that environmental element are unvarying.

Table 1 presents 13 potential subjective interactions across thermal, acoustic, visual and IAQ; but not all the subjective interactions have drawn the same amount of attention from researchers. **Table 1** summarizes the findings of Torresin et al., who conducted a systematic review of studies examining potential interactions [7]. For each subjective interaction, **Table 1** notes the number of studies that reported the

interaction and the number that found the interaction not to be discernible. Any achieved consensus is listed.

The interactions most discussed in prior studies are thermal environment affecting perceived IAQ and both sound and visual conditions impacting thermal sensation. Some of the most influential papers addressing these interactions are noted in the following paragraphs.

A series of studies by Fang et al. in 1998 reported that the acceptability of IAQ was significantly influenced by air temperature and humidity [8,9]. A significant inverse linear relationship was found between the acceptability and enthalpy of the air. Many subsequent studies yielded consistent results [10]. Torresin et al. reported no studies suggesting a contrary conclusion about this interaction.

A study by Tiller et al. indicated a slight influence of sound pressure on thermal comfort: a 7% increase in the RC (Room Criteria Curves) rating of the sound pressure would be required to produce a 1% decrease in the mean thermal comfort [11]. Another study by Pellerin et al. indicated that when the sound pressure increased from 60 dBA to 75 dBA, the thermal acceptability score decreased by approximately 3 points on a scale from -50 to +50 [12]. Other studies have obtained consistent conclusions that increasing sound pressure leads to a very slight loss of thermal satisfaction.

Another interaction reported in many studies is the impact of illuminance on thermal perception. Some studies have reported that the photic stimulation plays an indirect role in thermal comfort by affecting melatonin synthesis and release [13]. However, there is no consistent result in terms of the direction: four studies [14–17] found that exposure to low illuminance led to cooler feelings and two studies [18,19] found that it led to warmer feelings. A recent study by Yang and Moon reported that illuminance from 150 lx to 1000 lx didn't have impact on thermal sensation [20]. More evidence of interactions was found between color temperature and thermal sensation. A recent study by Toftum et al. indicated that a higher correlated color temperature was significantly associated with decreasing thermal sensation at the thermally neutral

condition [21]. It was found in another study that both self-report and observation indicated higher comfort under low color temperature [22]. A quantitative result was reported by Golasi et al. that effect of color temperature from cold light (11530 K) to warm light (1172 K) on thermal sensation equaled to more than one degree change in air temperature [23]. However, an early and highly cited study by Fanger et al. in 1977 indicated that the effect of color on thermal comfort is so small that it has hardly any practical significance [24]. While most prior studies found an effect of color temperature on thermal sensation, there is not consensus on the direction and magnitude of the effect.

Interactions other than those discussed above have been studied much less; and this gap has led some researchers to conduct studies that involve multiple interactions. Two examples were not included in the Torresin review. Yang & Moon exposed 60 subjects to a sets of indoor environment conditions and found multiple effects among thermal, acoustic and visual aspects, some of which were not reported previously [25]. Geng et al. varied temperature with other factors held constant and asked about subjects' satisfaction with thermal, acoustic, visual and IAQ conditions [26].

Table 1 Summary of reported subjective interactions based on a review by Torresin et al. [7] and studies by Yang & Moon [25] **and Geng et al.** [26]**.**

Factor	Perception	Number of studies reporting interaction	Number of studies reporting no interaction	Consensus
Thermal	IAQ	11	0	Higher temperature and humidity negatively impact perceived IAQ
Acoustic	Thermal	8	1	Higher sound pressure lowers thermal comfort
Visual (Color temperature)	Thermal	9	1	Color temperature has an impact on thermal sensation
Visual (Illuminance)	Thermal	6	1	No consensus
Thermal	Acoustic	6	3	No consensus
Thermal	Visual	4	0	No consensus
IAQ	Thermal	1	3	No interaction
Visual	Acoustic	1	1	No consensus
Acoustic	Visual	1	1	No consensus

Acoustic	IAQ	2	0	No consensus
IAQ	Acoustic	1	1	No consensus
Visual	IAQ	1	1	No consensus
IAQ	Visual	0	0	No consensus

1.2 Predicting overall satisfaction from individual factor satisfaction

Various weighting schemes have been proposed to combine satisfaction scores for factors of the indoor environment to arrive at a comprehensive IEQ satisfaction score, as summarized in **Table 2**. Reviews by Yang & Moon and Heinzerling et al. [25,27] found that previously proposed weighting schemes were inconsistent.

Most of the studies proposed their weighting schemes by linear regression analysis or presented the scheme in the form of a linear relationship, as summarized in **Table 2**. Cao, et al. used multivariate linear regression to model the relationship between overall satisfaction and satisfaction with the individual factors collected from 500 occupants in a field study in China [28]. A similar study was performed by Ncube & Riffat, who included no intercept term and adjusted model coefficients so that the their sum would be 100% [29]. Mui & Chan proposed a linear model of predicted dissatisfaction of overall IEQ with dissatisfaction of thermal comfort, IAQ and acoustics, which is equivalent to studies that assessed these variables with a satisfaction index [30]. Buratti, et al. proposed a combined index for the overall environment with thermal, acoustic and visual comfort based on votes from students [31]. The study by Mihai & Iordache in 2016 adopted the same approach and proposed an IEQ index containing four principle environmental factors [32]; while the researchers did not use linear regression, the proposed index was set in the form of a linear relationship. There are also a few studies that adopted a logistic regression model. Wong et al. proposed a logistic regression model of predicted overall acceptance of the indoor environment with satisfaction in thermal, visual, acoustic and IAQ based on survey data from offices in Hong Kong [33]. The satisfactory rating in the survey was simplified to two levels, unacceptable or acceptable. Another study by Fassio et al.

used both linear and logistical regression to predict overall satisfaction using satisfaction with factors employing a 4-level rating scheme [34]. The models proposed in the aforementioned studies did not find consistent weightings of the contributing factors.

There is a lack of sufficient information and discussion on the accuracy and interpretability of proposed models. In some studies model coefficients did not reach sufficient statistical significance [29,30,34]. One study did not provide significance test results [28]. It is also not clear that a linear regression model is appropriate for predicting overall satisfaction. Kim & DeDear adapted and experimented with Kano's satisfaction model, which was originally developed for marketing, to study the relationship between individual IEQ factors and overall satisfaction. The result identified nonlinear relationships between individual IEQ factors and overall satisfaction [35]. Notably, most previous studies are based on field studies. These study designs have the advantage of obtaining a large number of samples and reflecting real situations. However, they also have important limitations and potential confounders that are not always possible to discern, given the typically very limited information and the lack of control over measured conditions. It should also be noted that the statistically right answers do not necessarily inform understanding of the physical and physio-psychological mechanisms.

Table 2 Models relating overall satisfaction to satisfaction with specific factors of environmental quality

Studies	N	Method	R^2/Adj.R^2	Prediction model [a, b]
Cao et al., 2012	500	Multivariate linear regression	0.46	$S_O = 0.075 + 0.316S_T + 0.224S_A + 0.171S_V + 0.118S_{IAQ}$
Ncube & Riffat, 2012	68	Multivariate linear regression	0.94	$S_O = 0.30S_T + 0.18S_A + 0.16S_V + 0.36S_{IAQ}$
Mui & Chan, 2005	442	Multivariate linear regression	Not given	$DS_O = 0.42DS_T + 0.28DS_A + 0.09DS_{IAQ}$
Buratti et al., 2018	928	Self-reported	n/a	$S_O = 0.35S_T + 0.35S_A + 0.3S_V$
Mihai & Iordache, 2016	115	Self-reported	n/a	$S_O = \frac{0.251S_T + 0.241S_A + 0.244S_V + 0.263S_{IAQ}}{0.999}$
Fassio et al., 2014	17	Multivariate linear regression	Not given	$S_O \sim 0.02S_T + 0.31S_A + 0.56S_V + 0.12S_{IAQ}$ (9:45 am) $S_O \sim 0.33S_T + 0.18S_A + 0.38S_V + 0.10S_{IAQ}$ (11:30 am)
		Multivariate logistic regression	Not given	$S_O \sim 0.33S_T + 0.26S_A + 0.25S_V + 0.16S_{IAQ}$ (9:45 am) $S_O \sim 0.30S_T + 0.28S_A + 0.30S_V + 0.12S_{IAQ}$ (11:30 am)
Wong et al., 2008	293	Multivariate logistic regression	Not given	$S_O = 1 - \frac{1}{1 + \exp(15.02 + 6.09S_T + 4.74S_A + 3.70S_V + 4.88S_{IAQ})}$

a: S_O, overall satisfaction; DS_O, overall dissatisfaction; S_T, thermal satisfaction; DS_T, thermal dissatisfaction; S_A, acoustic satisfaction; DS_A, acoustic dissatisfaction; S_V, visual satisfaction; DS_V, visual dissatisfaction; S_{IAQ}, IAQ satisfaction; DS_{IAQ}, IAQ dissatisfaction.

b: For the study which gave only the coefficients of parameters and no original model equation, the model was expressed in an equation using ~

This paper reports an experimental study in which subjects were exposed to controlled and measured sets of IEQ conditions. The combined effects of the thermal environment, sound, light and IAQ on occupant satisfaction were quantified. The study aimed to address the following questions:

1. For which factors of environmental quality is satisfaction subjectively impacted by aspects of other factors and what are the mathematical forms and magnitudes of these interactions?
2. How does satisfaction with individual factors influence satisfaction with the indoor environment overall? Do the factor satisfactions combine in a linear manner to predict overall satisfaction or in some other manner?

2. Methods

2.1 Overview of experiment

The experiment was conducted in an IEQ laboratory at Chongqing University, China, in July and August 2018. The laboratory was configured to emulate an office setting. The laboratory is 6.9 m by 6.9 m by 2.8 m with an exterior wall, one interior door and two windows (on the shady side). **Figure 1** shows the layout of the laboratory and the positions of the subjects. Eight subjects were asked to work in the laboratory for 180 minutes for each designated set of indoor environmental conditions. At the start of the experiment, the subjects had 60 minutes to adapt to the established conditions, which is a method adopted in prior studies [11,36,37]. Subsequently, the subjects were asked to fill out an IEQ questionnaire twice, once at 120 min and once at 180 min. The experiment was carried out once each day from 9 AM to 12 PM to avoid possible impacts of different times of day. Eight subjects experienced all designated indoor environmental conditions. From beginning to end, subjects were blind to the indoor environmental index that they were experiencing. The experiment was approved by the Ethics Review Committee for Life Sciences Study of Central China Normal University with a registration number: CCNU-IRB-2018-012.

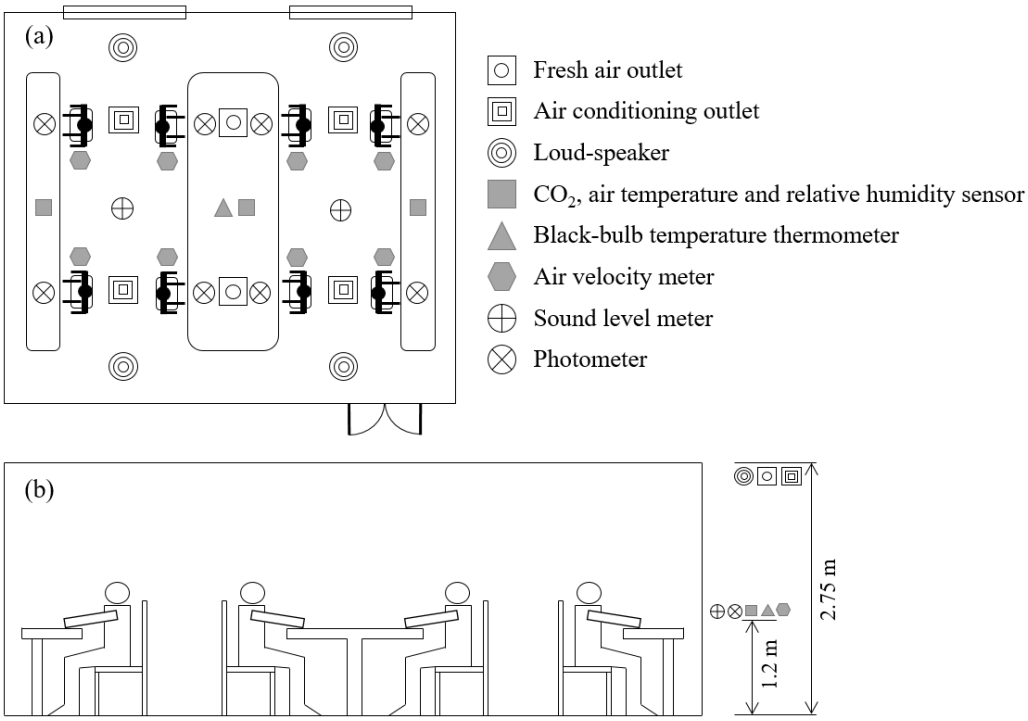

Figure 1 Layout of the office (a) floor plan (b) vertical cross-section view

2.2 Method for the experimental design

The experiment was designed to interlace different levels of IEQ factors. The goal was to include as many levels as possible of each IEQ factor to enable effects to be seen. However, this method would lead to excessive experimentation. The number of full-scale experimental designs could be 2401 if 7 levels were included for four factors, which is impractical. Therefore, a quadratic regression orthogonal design (QROD) was adopted to optimize the combination of different indoor environmental factors. QROD is developed from classic orthogonal design, which is designed for linear or non-linear regression analysis with a small experimental cost. The design allows the interaction terms to be detected in the regression analysis and proved to be efficient in previous study [38–40]. In QROD, to protect the orthogonality of experiment design, levels of factors were calculated by a specially designed algorithm, as shown in **Eq. 1** to **Eq. 3**. For the current study, based on a modified orthogonal array, a group of 25 experiments was assigned.

$$\Delta_j = (x_{j1} - x_{j2})/2r \tag{1}$$

$$x_{0j} = (x_{j1} + x_{j2})/2 \tag{2}$$

$$x_{kj} = k \times \Delta_j + x_{0j}, k = -r, -1, 0, 1, r \tag{3}$$

Where x_{j1} is upper limit of the factor and x_{j2} is lower limit of the factor, r is adjustment factor which equals to 1.546 in this study, x_{0j} is the central level of the factor, x_{kj} is the k level of the factor.

Given that the extreme value of each parameter was to be simulated only once in the orthogonal design, six experiments were added to provide duplicates of extreme conditions. The added experiments were assigned by uniform design, which is another optimization method proposed by Kaitai and Yuan [41]. Uniform design is a Quasi-Monte Carlo method that selects a few representative test points to reflect the subject characteristics. This method has been applied in similar studies and proved to be efficient [42–44]. This process yielded a total of 31 experiments, as shown in Error! Reference source not found.. For each parameter, 7 levels were included. The order of experiments was decided by randomly generated numbers. Eight subjects experienced each condition simultaneously to avoid possible errors caused by reproducing environmental conditions.

Table 3 Simulated indoor environmental conditions

Code	Date	Intended PMV	Measured PMV	Intended Sound pressure （dBA）	Measured Sound pressure （dBA）	Intended Illuminance （Lx）	Measured Illuminance （Lx）	Intended CO_2 (PPM)	Measured CO_2 (PPM)
1	8.13	0.97	0.98 (0.10)	60.6	60.5	259	264	1323	1374 (47)
2	8.21	0.97	0.87 (0.11)	60.6	60.4	259	268	677	722 (55)
3	8.9	0.97	1.26 (0.13)	60.6	60.9	841	852	1323	1224 (76)
4	7.23	0.97	1.25 (0.12)	60.6	60.7	841	842	677	747 (42)
5	8.4	0.97	0.86 (0.17)	44.7	44.7	259	257	1323	1440 (53)
6	8.20	0.97	0.99 (0.14)	44.7	44.4	259	255	677	842 (65)
7	7.27	0.97	0.88 (0.17)	44.7	44.8	841	847	1323	1315 (54)
8	8.14	0.97	0.73 (0.15)	44.7	44.5	841	841	677	865 (51)
9	7.22	-0.97	-1.01 (0.12)	60.6	60.8	259	251	1323	1252 (49)
10	8.3	-0.97	-0.75 (0.13)	60.6	60.4	259	248	677	689 (37)
11	8.23	-0.97	-1.08 (0.14)	60.6	60.4	841	829	1323	1331 (68)
12	7.25	-0.97	-0.92 (0.12)	60.6	60.6	841	853	677	716 (42)
13	7.21	-0.97	-1 (0.15)	44.7	44.9	259	250	1323	1360 (54)
14	8.15	-0.97	-1.08 (0.14)	44.7	44.5	259	252	677	703 (39)
15	8.5	-0.97	-1.06 (0.12)	44.7	44.3	841	835	1323	1376 (67)
16	8.24	-0.97	-0.69 (0.16)	44.7	44.5	841	839	677	697 (42)
17	7.26	1.5	1.36 (0.11)	52.5	52.7	550	556	1000	1214 (55)
18	8.18	-1.5	-1.63 (0.12)	52.5	52.7	550	542	1000	1014 (64)
19	8.26	0	-0.02 (0.13)	65	64.9	550	559	1000	950 (49)
20	8.7	0	-0.03 (0.15)	40	40.4	550	559	1000	990 (53)
21	8.27	0	-0.28 (0.11)	52.5	52.4	100	104	1000	1006 (62)
22	8.19	0	-0.05 (0.13)	52.5	52.4	1000	997	1000	1070 (51)
23	8.11	0	-0.2 (0.15)	52.5	52.3	550	554	1500	1450 (42)

24	8.25	0	0.01 (0.14)	52.5	52.8	550	552	500	545 (21)
25	8.28	0	0.03 (0.11)	52.5	52.5	550	542	1000	1034 (54)
26	8.6	-0.5	-0.45 (0.10)	48.5	48.8	700	694	830	756 (39)
27	8.17	-0.5	-0.53 (0.09)	56.5	56.9	700	709	1160	1180 (69)
28	7.31	0.5	0.61 (0.08)	48.5	48.7	400	402	830	848 (42)
29	7.30	0.5	0.65 (0.11)	56.5	56.3	400	391	1160	1170 (34)
30	8.29	-1.5	-1.65 (0.09)	65	64.9	1000	1012	1500	1468 (45)
31	8.16	1.5	1.39 (0.08)	40	40.6	100	94	500	612 (22)

Note: The Standard Deviation (SD) is presented in the bracket for measured PMV and CO_2 concentration. Illuminance and sound pressure remained basically unchanged during each test.

2.3 Method for thermal environmental simulation

Predicted Mean Vote (PMV), a combination index for indoor thermal comfort proposed by Fanger [45], was adopted as the index of the indoor thermal environment. The PMV levels in the experiment were set to targets of -1.5, -0.97, -0.5, 0, 0.5, 0.97 and 1.5, ranging from slightly cold to slightly warm according to the ASHRAE thermal comfort scale [46]. Four fan coil units installed in the office were used to control indoor air temperature and air speed. Fan coil units were started one hour before and operated through each experiment to maintain a steady indoor thermal condition. Three temperature and relative humidity data loggers (Model UX100-003 by Onset HOBO) were placed on three working desks near the subjects to continuously measure and record dry-bulb air temperature and relative humidity. One black-bulb thermometer was placed on the working desk in the center of the office to continuously measure and record the indoor black-bulb temperature. Indoor air speeds were measured before each experiment with hot-wire anemography, and the air speeds remained below 0.2 m/s throughout the entire experiment. The office window was obscured by thick light-blocking curtains to minimize the effects of sunlight. The average difference between black-bulb temperature and air temperature was 0.32 degree throughout the experiment. During the experiment, all subjects were asked to wear uniform clothing provided by the experiment organizer, including a short-sleeve knit sport shirt (0.17 clo) and thin straight trousers (0.15 clo). Subjects wore their own shoes (0.02 clo), ankle-length athletic socks (0.02 clo) and underwear (0.04 clo). In addition, all subjects used the same standard office chair (0.10 clo). The thermal insulation values (clo) cited above are according to ASHRAE standard 55 [46]. Therefore, the total thermal insulation of each subject was 0.5 clo.

2.4 Method for acoustic environmental simulation

Sound pressure was used as the index for the acoustic environment. The sound pressure range was set

from 40 dBA to 65 dBA. Forty dBA is considered to be the high level for a multi-person office according to the Chinese standard [47], and 65 dBA is a common noisy condition adopted by a previous study [48]. Background noise in the office was mainly from the fan coil units and was stable at approximately 37 dBA. The noise outside the window was effectively isolated by three-layer insulating glass. The door of the office was tightly sealed with sealing strips. Adjacent rooms were unoccupied during the experiment. An edited record of fan noise was played by four loudspeakers to simulate air conditioning noise during the experiment. Loudspeakers were placed on the celling and maintained the intended indoor sound pressures under remote control. Two integrating sound level meters (Model 1353S by TES Electrical Electronic Corp.: http://www.tes.com.tw/) were symmetrically placed in the office to continuously measure and record the indoor sound pressure, as shown in **Figure 1**. The research subjects were not allowed to listen to music, watch videos or speak during the experiment.

2.5 Method for lighting environment simulation

Illuminance was chosen as the index for the visual environment. The range of illuminance was set to extend beyond the range of the Chinese lighting design standard for an office setting [49]: using a range of 100 Lx to 1000 Lx to represent dim to bright conditions. Forty of the same LED lamps, which had adjustable brightness, were uniformly installed on the celling in the office. Lamps were controlled by six adjustable switches to maintain the designated illuminance on a working desk. Previous studies have indicated that the correlated color temperature of lamps has an impact on the perceived thermal environmental quality [21,22]. The correlated color temperature was fixed at 4000 K during the entire experiment, which is within the guideline range for an office according to the Chinese lighting design standard [49]. Illuminance on a working desk was measured with a photometer (Model 1399 by TES) during the experiment. Sunlight was completely blocked by thick light-blocking curtains over the windows to minimize external disturbance.

2.6 Method for IAQ simulation

The concentration of CO_2 was designated as the index for IAQ [28,33,34]. (The use of CO_2 as an IAQ index was found to be questionable, as discussed later.) The range of CO_2 concentration in the experiment was from 500 PPM (almost fresh air) to 1500 PPM (1.5 times the limit value) [50]. The chamber was ventilated with outdoor air at the rate needed to achieve the 500 PPM CO_2 condition. A fan with frequency conversion adjustment was controlled based on indoor concentration of CO_2. In conditions of high designated CO_2 concentration, two compressed gas cylinders filled with chemically pure CO_2 were controlled with relief valves to slowly release CO_2 into the air [51,52]. The compressed gas cylinders were linked to a return air inlet by a soft tube so that the CO_2 diffused evenly into the air. Three CO_2 sensors (Telaire Model 7001) were placed on three working desks to continuously measure and record the concentration of CO_2. The readings were checked every 10 minutes to ensure the intended concentration and avoid releasing excessive CO_2. Smelly foods and perfume were forbidden in the experiment.

All instruments used in this study were calibrated by Chongqing Academy of Metrology and Quality Inspection.

2.7 Subjects

The eight subjects, four male and four female, were postgraduate students majoring in The Built Environment. They had a mean±standard deviation (SD) age of 23±1 years, height of 168±3 cm and weight of 60±4 kg. Body mass index (BMI) is the ratio of weight to height and has been used as a common index of human obesity. According to the Chinese standard, a BMI between 18.5 and 24.0 kg/m^2 is recognized as normal [53]. All subjects were within the normal BMI range, which avoided possible errors in perceived thermal comfort caused by obesity [54]. None of the subjects smoked or consumed excessive alcohol and none had any history of cardiovascular disease, mental disease or disabilities. Before the start of

the experimental trials, the procedure was clearly introduced to all subjects, and two training experiments were carried out in which the subjects were asked to follow all of the procedures but no data were collected. During the experiments, subjects were required to remain seated, except when they needed to use restroom, in order to maintain a steady metabolic rate at 1.0 Met. Subjects were allowed to bring laptops and reading material. Reading, writing, typing and drinking of room temperature water that was provided were allowed. Eating, speaking, drinking other beverages and listening to music or watching videos were forbidden. Subjects were asked to not participate in strenuous exercise and to acquire adequate sleep during the night before each experiment. A grant of 1000 RMB was given to each subject for their participation.

2.8 Method for subjective measurement

A questionnaire was used to collect a subject's perceived indoor environment quality and satisfaction. The questionnaire contained two major parts. The first asked about the subjects' perception of individual indoor environmental factors, such as thermal sensation vote (TSV) and brightness sensation vote. Thermal sensation was voted with a 7-point scale while sensations for bright, noise and other environmental aspects were voted with a 10-point scale. The second asked about satisfaction with individual environmental factors and overall environment, using a 10-point rating scheme. Below are examples of thermal sensation vote, brightness vote and satisfaction vote in the questionnaire.

1. Please describe your thermal feeling using a rating from -3 to 3.

-3	-2	-1	0	1	2	3
Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot

2. Please describe the brightness using a rating from 1 to 10.

1 - 2	3 - 4	5	6	7 - 8	9 - 10
Extremely dim	Dim	Slightly dim	Slightly bright	Bright	Extremely bright

3. Please describe your satisfaction with the indoor thermal environment using a rating from 1 to 10.

1 - 2	3 - 4	5	6	7 - 8	9 - 10
Very dissatisfied	Fairly dissatisfied	Slight dissatisfied	Slight satisfied	Fairly satisfied	Very satisfied

2.9 Statistical analysis method

Correlation analysis was applied to identify any linear association between two variables. However, correlation analysis may lead to incorrect conclusions when another factor is numerically related to both variables. Thus, partial correlation analysis was applied when identifying correlations between satisfaction and environmental parameters. When the partial correlation between one environmental parameter and satisfaction was analyzed, other parameters were introduced as control variables, and their effects were removed. Regression analyses were performed to quantitatively explore the relationships of indoor environmental parameters to satisfaction with each of the four factors of IEQ, and the relationship between factor satisfactions and overall satisfaction. Several types of regression analyses, including multiple linear regression and multiple nonlinear regression, were explored. All statistical analyses were performed with the R programming language [55].

3. Results

3.1 Measured indoor environmental parameters

Table 3 presents the intended and measured indoor environmental parameters and shows that the intended conditions were achieved with just a few substantial discrepancies.

3.2 Subjective interactions between environmental factors

Subjects voted twice for each simulated environmental condition, thus 62 rounds of votes for 31 environmental conditions were collected and used in the partial correlation analysis and regression analysis. **Table 4** presents results of the partial correlation analysis investigating the relationships between environmental parameters and satisfaction with each factor of IEQ. Significant relationships ($P < 0.05$) are shown in bold.

Table 4 Summary of partial correlation analysis

Factor satisfaction	Varied indicator [a]	Correlation coefficient	P
Thermal satisfaction [b]	PMV^2	-0.914	**<0.001**
	Sound pressure	-0.144	0.275
	Illuminance	0.034	0.796
	CO_2	-0.138	0.299
Acoustic satisfaction	PMV	0.031	0.816
	Sound pressure	-0.958	**<0.001**
	Illuminance	-0.283	**0.030**
	CO_2	-0.171	0.194
Visual satisfaction	PMV	-0.235	0.073
	Sound pressure	-0.076	0.570
	Illuminance	0.795	**<0.001**
	CO_2	0.07	0.599
IAQ satisfaction	PMV	-0.811	**<0.001**
	Sound pressure	-0.345	**0.007**
	Illuminance	0.232	0.077
	CO_2	-0.094	0.477

a: The degrees of freedom are 57.

b: PMV^2 was used instead of PMV in partial correlation analysis on thermal satisfaction because the relationship between PMV and thermal satisfaction has been found to be quadric.

3.2.1 Thermal satisfaction

The relationships between thermal satisfaction and each of the four environmental indicators are shown in **Figure 2**.

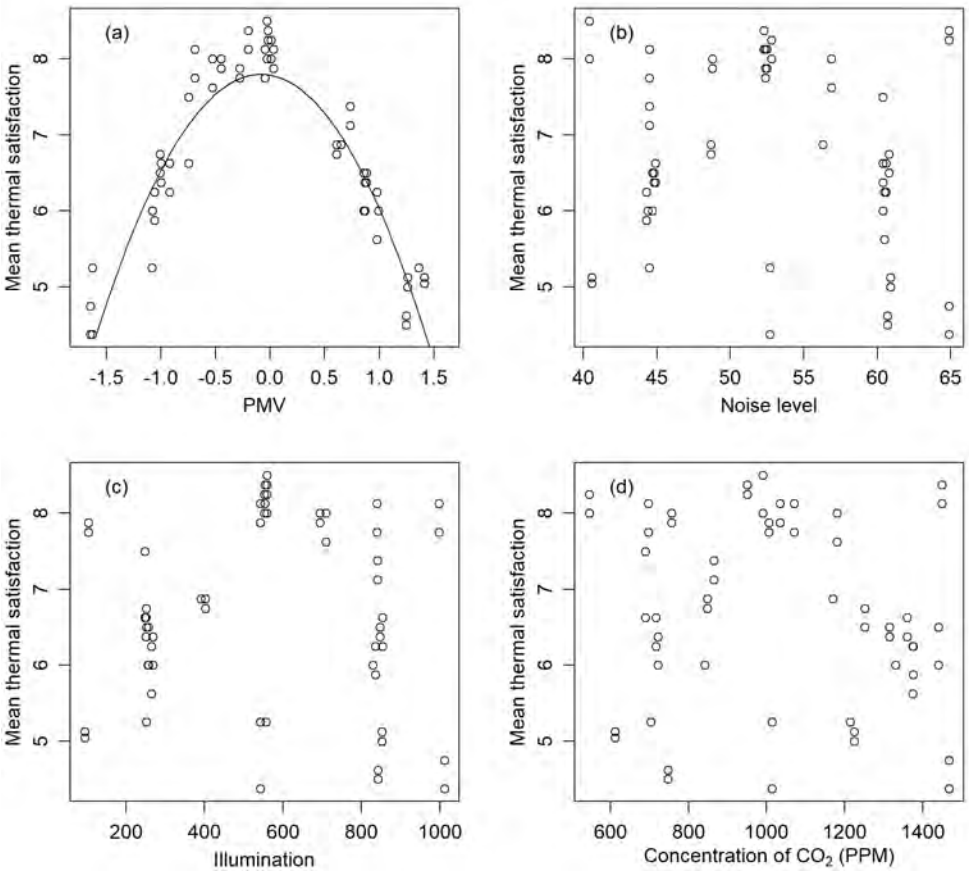

Figure 2 Thermal satisfaction and environmental parameters

The partial correlation analysis (**Table 4)** found that thermal satisfaction was significantly correlated with PMV^2, but no significant correlation was detected with other parameters. **Figure 2** shows the nonlinear relationship between PMV and thermal satisfaction, which is approximate to a quadratic equation. To quantitatively describe the relationship, a single variable nonlinear regression was performed to identify the predicted average thermal satisfaction (S_T) with PMV (P), as shown in **Eq. 4**.

$$S_T = 7.88 + 0.254P + 1.51P^2 \tag{4}$$

The regression results indicate that all coefficients in the model are significant and the residual standard error (RSE) of the model is 0.444. The regression model fit is shown in **Figure 2**. Neutral conditions provide the highest thermal satisfaction, which decreases with the absolute value of PMV. Thermal satisfaction spanned from roughly 8 to 4, corresponding to fairly satisfied to fairly dissatisfied.

3.2.2 Acoustic satisfaction

Figure 3 shows a linear relationship between sound pressure and mean acoustic satisfaction, which has been reported in many previous studies [28,30]. Independent of the influence of other parameters, a 1 dBA increase in sound pressure led to a 0.177-point decrease in the acoustic satisfaction score.

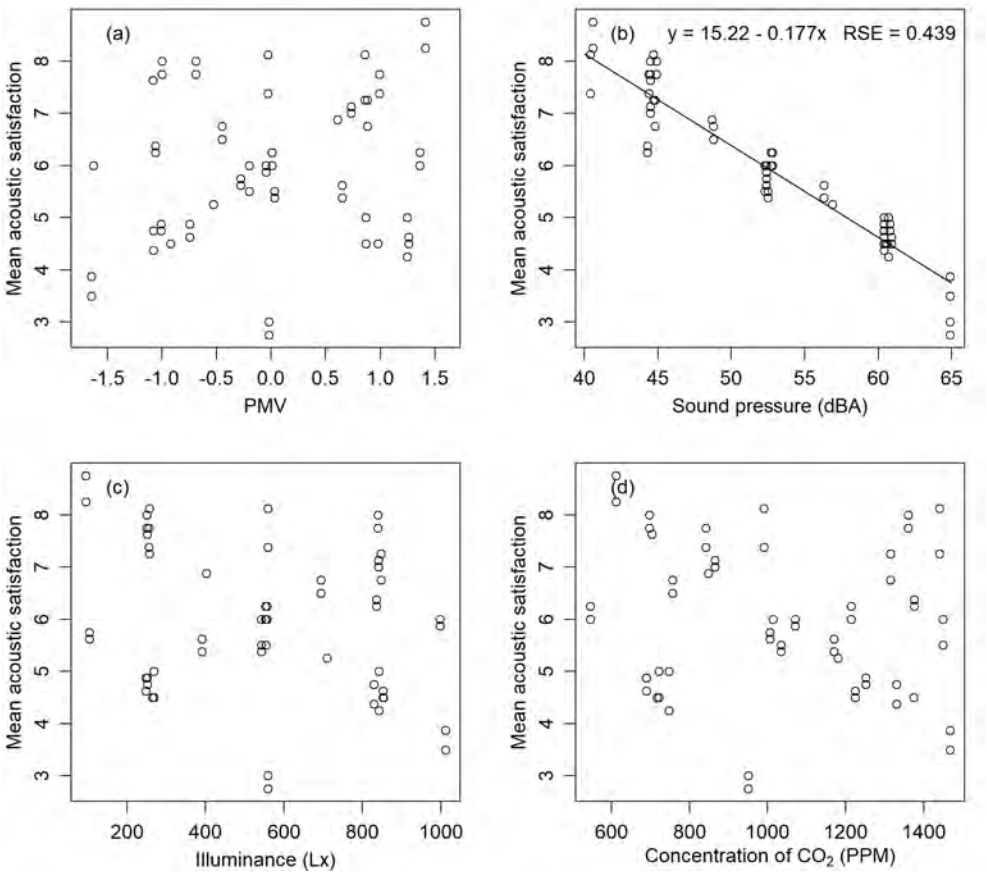

Figure 3 Acoustic satisfaction and environmental parameters

The partial correlation analysis indicates that acoustic satisfaction is also influenced by illuminance (P=0.03) when the sound pressure is low, as shown in **Figure 4**. When the sound pressure was approximately 45 dBA, lower illuminance conditions (approximately 259 Lx) yielded higher acoustic satisfaction than higher illuminance conditions (approximately 840 Lx). Varying illuminance had no significant impact on acoustic satisfaction when the sound pressure was approximately 60 dBA. An explanation is that the effect of illuminance on acoustic satisfaction is influenced by sound pressure, which is generally defined as the

'moderation effect'.

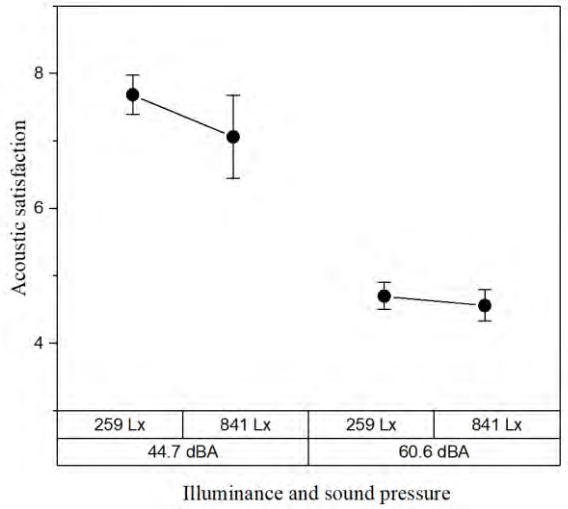

Figure 4 Acoustic satisfaction under different illuminance and sound pressures

A regression model is proposed based on the previous analysis, as shown in **Eq. 5**. Average acoustic satisfaction S_A is determined by sound pressure SP, illuminance I and interaction term $SP \times I$. The interaction term represents the moderation effect.

$$S_A = 16.8 - 0.203SP - 2.92 \times 10^{-3}I + 4.66 \times 10^{-5}(SP \times I) \quad (5)$$

Multiple nonlinear regression was performed to estimate the coefficients, which are all significant ($P<0.05$). The RSE of the model is 0.384, which is less than the RSE of the linear regression model (0.439) that included only sound pressure, i.e., without illuminance and the interaction term. This result supports the finding of a moderation effect among sound pressure, illuminance and acoustic sensation.

The regression model can be described by a contour map, as shown in **Figure 5**. When the sound pressure is high, contour lines are vertical since the sound pressure is the only influencing factor. When the sound pressure is low, contour lines curve, indicating the illuminance effect. Quantitatively, when the sound pressure is fixed at 45 dBA, every 500 Lx illuminance decrement leads to a 0.41 out of 10 increase in acoustic satisfaction. As I and $SP \times I$ have smaller coefficients than SP in the model, the relationship between sound pressure and average acoustic satisfaction can be approximated as a linear relationship under most

circumstances.

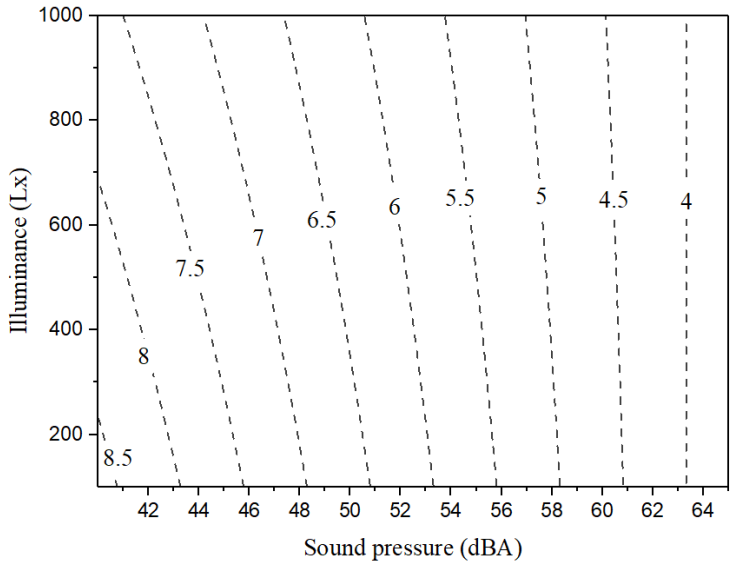

Figure 5 Contour map of illuminance, sound pressure and acoustic satisfaction level

3.2.3 Visual satisfaction

The partial correlation analysis indicates that illuminance was the only parameter that affected the subjects' visual satisfaction (**Table 4)**. But the relationship was not linear over the full range of illuminance, as shown in **Figure 6**. When the illuminance was below 550 Lx, visual satisfaction increased significantly with illuminance. When illuminance was above 550 Lx, visual satisfaction remained steady even when the illuminance continued to increase. Additionally, paired t-test showed no significant difference among visual satisfactions under illuminances of 550 Lx, 700 Lx, 840 Lx and 1000 Lx (P=0.219). The correlation between satisfaction and illuminance has the form of a Boltzmann distribution, as shown in **Eq. 6**. Nonlinear regression was performed to estimate regression model coefficients. All coefficients in the regression model are significant. **Figure 6** illustrates the regression model and shows good agreement between the model and actual data points.

$$S_V = 7.80 - \frac{4.87}{1+\exp\left(\frac{I-210}{86.2}\right)} \quad (6)$$

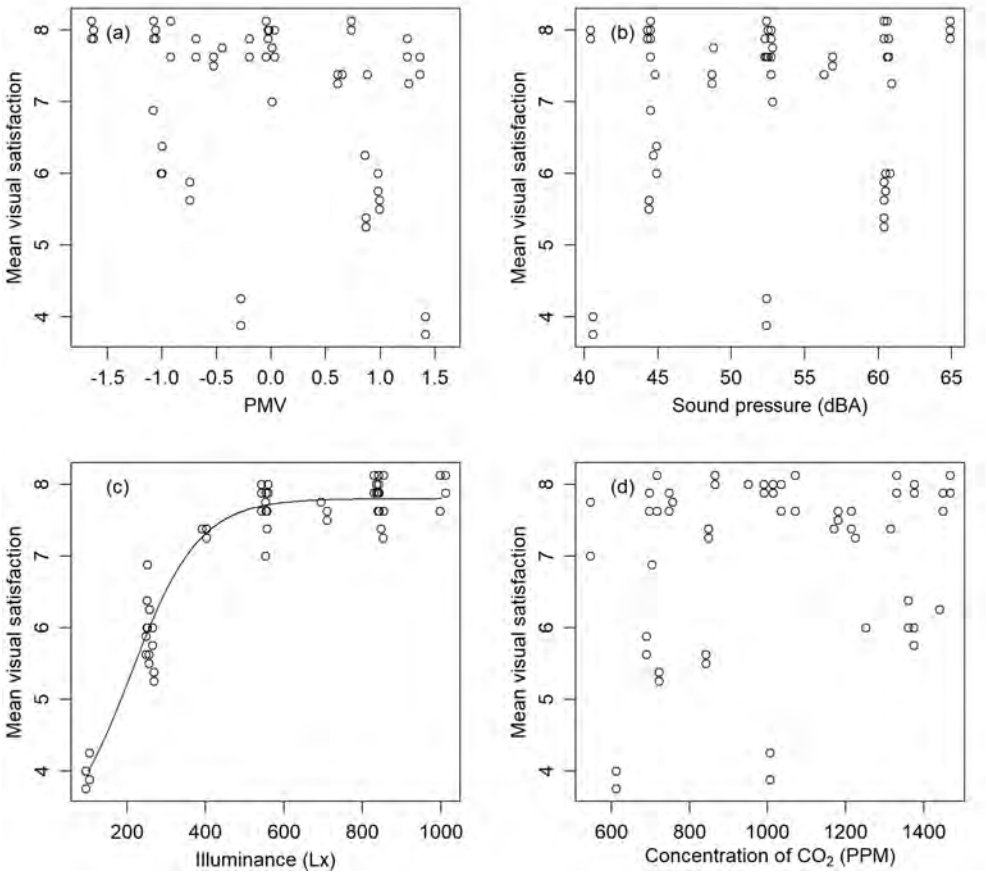

Figure 6 Visual satisfaction and environmental parameters

3.2.4 IAQ satisfaction

The IAQ satisfaction scores reported for variations of each environmental parameter are shown in **Figure 7**, which reveals a clear relationship to PMV but no obvious relation to any other parameter, including CO_2. The partial correlation analysis reinforces that PMV was the key factor influencing IAQ satisfaction in this experiment, as it had a high correlation coefficient and very low P-value (**Table 4**). When PMV increased from 0 to 1.5, IAQ satisfaction decreased markedly. The relationship fits an exponential form, as shown in **Figure 7**. Subjects reported higher IAQ satisfaction under cold environment conditions than under warm conditions, whereas, the simulated cold environment conditions didn't have better IAQ than warm conditions objectively.

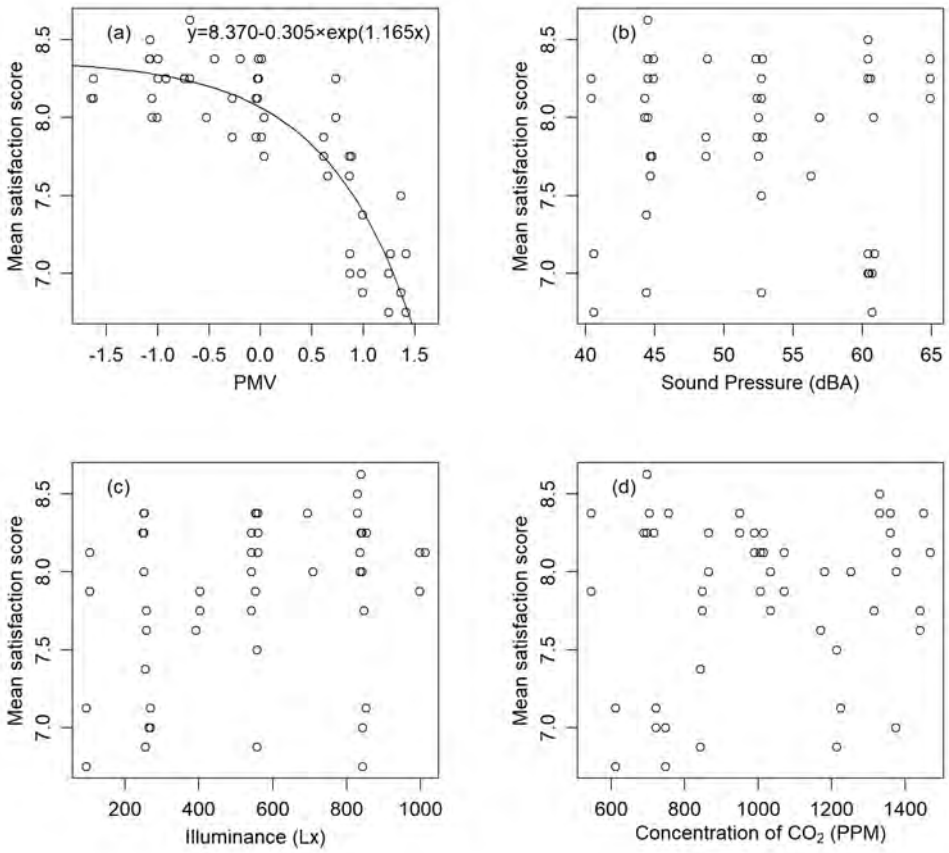

Figure 7 IAQ satisfaction and environmental parameters

The partial correlation analysis also identified a significant inverse relationship between sound pressure and IAQ satisfaction. The relationship is not apparent in the scatterplots because the influence of sound pressure is much smaller than the influence of PMV. The relationship of IAQ satisfaction (S_{IAQ}) to PMV (P) and sound pressure (SP) is quantified with the non-linear regression model presented in **Eq. (7)**.

$$S_{IAQ} = 8.97 - 0.326 \times \exp(1.10P) - 0.011SP \tag{7}$$

The significance level of the coefficient for the SP term is 0.06, indicating sound pressure likely impacts IAQ satisfaction; but the influence appears small. According to the model, every 10 dBA increment of sound pressure leads to a 0.1 out of 10 IAQ satisfaction decrease when the PMV is fixed, which is much slighter than the effect of PMV.

3.3 Overall satisfaction

Table 5 presents the results of both simple and partial correlation analyses to identify relationships between overall environmental satisfaction and satisfaction with thermal, acoustic, illuminance and indoor air quality factors. And **Figure 8** plots the rank order of overall satisfaction with corresponding satisfaction scores for each factor and the mean of the four factor scores for each test. The correlation analysis indicates that satisfaction with each factor of the environment contributes to the overall satisfaction in a positive way, which was expected and is consistent with the observations of previous studies [25]. The correlation coefficients do not represent the relative importance of each factor because they have not been normalized for this purpose, and many of the factor satisfaction values are correlated. The negative partial coefficient of IAQ satisfaction is discussed in the next subsection. **Figure 8** shows that overall satisfaction is always lower than the average of the satisfaction scores for the four factors. It is also closely correlated with and similar to the lowest of the individual factor satisfactions.

Table 5 Correlation coefficients between factor satisfactions and overall satisfaction

Variables	Thermal satisfaction	Acoustic satisfaction	Visual satisfaction	IAQ satisfaction
Correlation	0.594***	0.630***	0.371***	0.412**
Partial correlation	0.802***	0.898***	0.791***	-0.113

Note: *** P<0.001; ** P<0.01; * P<0.05.

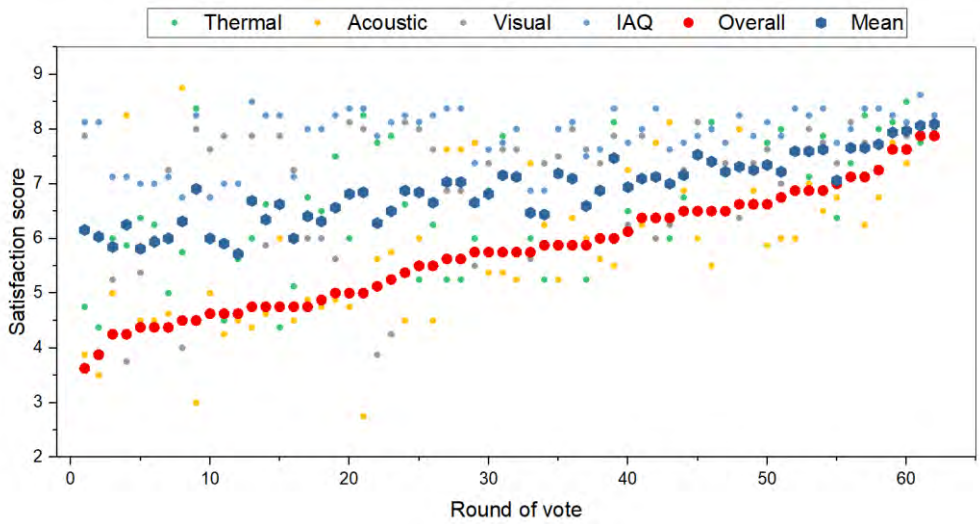

Figure 8 Factor satisfactions, overall satisfaction and mean of four factor satisfactions, sorted by overall satisfaction

3.3.1 Multiple linear regression model

A multiple linear regression analysis was conducted to identify the correlation coefficients between satisfaction with each factor of environmental quality and overall satisfaction. The linear model was most commonly used in previous studies [28,29,34]. In the linear model, the coefficient of each independent variable (factor satisfaction) is constant and represents the contribution to the dependent variable (overall satisfaction S_O), as shown in **Eq. 8**.

$$S_O = a + bS_T + cS_A + dS_V + eS_{IAQ} \tag{8}$$

Table 6 presents the results of the OLS multiple linear regression. Consistent with the partial correlation analysis result shown in **Table 5**, the coefficient of IAQ satisfaction is negative, indicating an inverse relationship between IAQ satisfaction and overall satisfaction. This result is inconsistent with the rational expectation that higher IAQ satisfaction should have a positive impact on an occupant's comfort, which has been proven in many previous studies [1,2]. In fact, the reason for this incorrect conclusion is multicollinearity, a phenomenon in which one predictor variable in a multiple regression model can be linearly predicted from other variables with a substantial degree of accuracy. In this study, both IAQ and

thermal satisfaction were found to be mainly influenced by PMV. This result leads to an extremely significant linear correlation between these variables ($P<0.001$), meaning that IAQ satisfaction can be predicted from thermal satisfaction.

IAQ satisfaction was thus removed as a variable, and a summary of the revised linear regression model is shown in **Table 6**. The R^2 value was reduced by 0.03, and the RSE increased by 0.002 compared to the model that includes IAQs. This is expected because the model contains fewer coefficients, but loss of prediction accuracy is negligible. The coefficients of all variables are significant and positive, indicating that satisfaction with each factor of environmental quality positively contributes to overall satisfaction. Note this finding may not apply when another IAQ parameter which objectively impacts IAQ satisfaction is involved.

Given the significant correlation between the mean of the factor satisfactions and overall satisfaction, an arithmetic mean model was assessed. The form of the model is shown in **Eq. 9** and parameter values are in **Table 6**. Since IAQ satisfaction was not independent of thermal satisfaction, the model used only the satisfaction scores for thermal, acoustic and visual factors. Actually, the arithmetic mean model is a special linear model with only one feature, so it is under-fitting.

$$S_O = \mathrm{a} + \mathrm{b} \times (S_T + S_A + S_V)/3 \tag{9}$$

3.3.2 Nonlinear regression model

A predictive model based on the geometric mean of the factor satisfactions is shown in **Eq. 10**.

$$S_O = f(S_T, S_A, S_V) = \mathrm{a} + \mathrm{b} \times \sqrt[3]{S_T \times S_A \times S_V} \tag{10}$$

The geometric mean was considered because it has the characteristic of being always lower than the arithmetic mean except when all factors have equal values, and it is then equal to the arithmetic mean. The geometric mean model contains an interaction term of three parameters, which is not included in the linear model. A nonlinear regression was performed to estimate parameters for the model, and results are shown in

Table 6. The geometric mean model has better prediction accuracy than the linear regression model, as the RSE is reduced by 14 percent. Considering that it contains only half the number of coefficients and achieves a better prediction accuracy, the geometric mean model appears promising as an improvement over the linear model for predicting overall satisfaction from satisfaction with IEQ factors.

Table 6 Summary of regression models for predicting overall satisfaction with individual satisfaction

Regression models	DF	Coefficients	Estimate	Std. Error	Sig.[a]	R^2	Adj R^2	RSE
Multiple linear model	57	a	-2.384	0.674	***	0.911	0.905	0.326
		b	0.463	0.040	***			
		c	0.529	0.031	***			
		d	0.423	0.041	***			
		e	-0.136	0.103	ns			
Multiple linear model without S_{IAQ}	58	a	-3.106	0.390	***	0.908	0.903	0.328
		b	0.438	0.035	***			
		c	0.525	0.031	***			
		d	0.401	0.037	***			
Arithmetic mean model	60	a	-3.282	0.405	***	0.893	0.892	0.348
		b	1.381	0.061	***			
Geometric mean model	60	a	-2.656	0.300	***	n/a	n/a	0.282
		b	1.306	0.046	***			

a: ***, P<0.001; **, P<0.01; *, P<0.05; ns, P>0.05.

4 Discussion

4.1 interactions between individual indoor environments

In this study, the effects of PMV, sound pressure, illuminance and concentration of CO_2 on satisfaction with individual factors of IEQ were investigated. The results are summarized in **Figure 9**. Solid lines represent dominant effects, dashed lines represent subordinate effects and dotted lines represent adjusting effects. An arrow of dominate effect or subordinate effect started from an environmental parameter and pointed to a factor satisfaction, which means this parameter had a dominate or subordinate effect on the factor satisfaction; an arrow of adjusting effect started from a parameter and pointed to an arrow of dominate or subordinate effect, which means this effect was adjusted by the parameter. It was confirmed that the

thermal environment simulated for this experiment according to the scale of PMV also satisfied the participating subjects in this experiment: the highest thermal satisfaction was reported when PMV was close to 0 and satisfaction dropped with the absolute value of PMV. This finding is in accordance with previous studies [26,28]. Acoustic satisfaction was dominated by sound pressure, as expected. An interaction between the acoustic environment and visual environment was detected. A darker environment led to the perception of a quieter environment and increased acoustic satisfaction. This effect was adjusted based on sound pressure. Visual satisfaction was dominated by illuminance with brighter conditions producing higher visual satisfaction. The interaction between thermal conditions and IAQ satisfaction indicated by many previous studies [8,9] was verified again by this study: subjects reported lower satisfaction with IAQ under warmer conditions (PMV>0), and the effect was dominant. A slight negative effect of sound pressure on IAQ satisfaction was also found in the current study despite the effect not being reported previously.

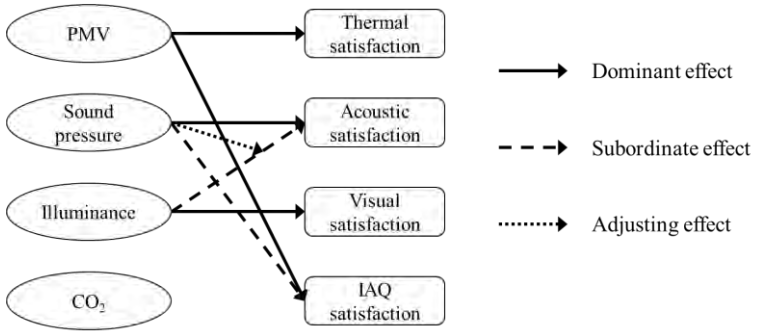

Figure 9 Effects of environmental conditions on reported satisfaction with individual IEQ factors

CO_2 was chosen as the index for IAQ in this study, but it had no significant impact on IAQ satisfaction – even at 1500 PPM, which is 1.5 times the limit value in the Chinese standard [50]. Given that it didn't impact perceived IAQ, it would also not be expected to impact satisfaction of other environmental factors. We chose CO_2 because it is a common parameter for IAQ in standards and guidelines set by international bodies [56] and it has been adopted as an index for IAQ in many previous field studies. Several recent studies have found that elevating CO_2 independently from outdoor air ventilation – as we did in this study – can

negatively impact performance on complex cognitive tasks [51,57], whereas others have found that CO_2 did not impact performance on simpler cognitive tasks or perceived IAQ [52,58]. The result of the current study aligns with the latter findings. In future controlled studies of IEQ interactions, it is recommended to use an environmental parameter other than CO_2 to represent IAQ conditions.

The parameter range has a great impact on detecting interactions. Interactions are relatively small in most cases compared with the effects of corresponding environmental factors [21,25]. Some interactions may only be apparent when the aspect of one factor that is impacting satisfaction with another factor varies over a wide range. For example, Pellerin and Canads exposed subjects to sound pressures of 35 dBA, 60 dBA and 75 dBA and found that thermal unpleasantness increased with the sound pressure [12]. The narrower range of sound pressures used in our study (40-65 dBA) may explain why no interaction was detected between thermal satisfaction and acoustic environment. However, any interaction that occurs only under conditions that are infrequently encountered in real buildings has less practical significance.

Exposure time is another factor influencing detection of interactions; some previous studies chose to continuously change indoor environmental conditions during the experiment, rather than to expose subjects over an extended duration. This approach enables more environmental conditions to be tested in a study with less time expense. However, subjects may have different perceptions when indoor environment conditions change frequently or continuously than they do when exposed to the conditions over an extended period. Changing conditions may lead to a comparative effect where subjects compare a present condition to the recent prior condition are thus experience satisfaction or dissatisfaction at a condition that would be experienced differently under sustained exposure.

4.2 Regression model of overall satisfaction with factor satisfaction levels

The geometric mean model illustrates different correlations between environmental satisfaction levels

compared with the linear regression model. The linear relationship was interpreted in a way that the contribution of satisfaction with individual environmental factor to overall satisfaction is isolated and constant. A classic framing of the linear relationship is that "for a unit increase or decrease in thermal comfort, the IEQ index increases or decreases by 0.3 respectively, all else being equal" [20].

In the geometric mean model, the relationship of one factor to the others can be interpreted by partial derivative. For instance, the partial derivative of S_T to S_O is determined by the ratio of ${S_T}^2$ to $S_V \times S_A$, which represents the relative level of thermal satisfaction to other factor satisfactions, as shown in **Eq. 11**. **Figure 10** presents the correlation between S_T and the partial derivative of S_T to S_O when S_V and S_A are fixed at 7. A partial derivative could be recognized as the rate of change with one factor when other factors are fixed. Therefore, when thermal satisfaction decreases, the partial derivative of thermal satisfaction increases, which means a unit change in thermal satisfaction has a greater impact on overall satisfaction. When thermal satisfaction increases, the result is the opposite. This result also applies to visual satisfaction and acoustic satisfaction as they all have the same form of partial derivative. This characteristic explains why the geometrical model better fits the experimental data because the measured overall satisfaction level is always closely correlated to the lowest individual environmental satisfaction.

$$f'_{S_T}(S_T, S_A, S_V) = 0.425 \div \sqrt[3]{\frac{{S_T}^2}{S_V \times S_A}} \tag{11}$$

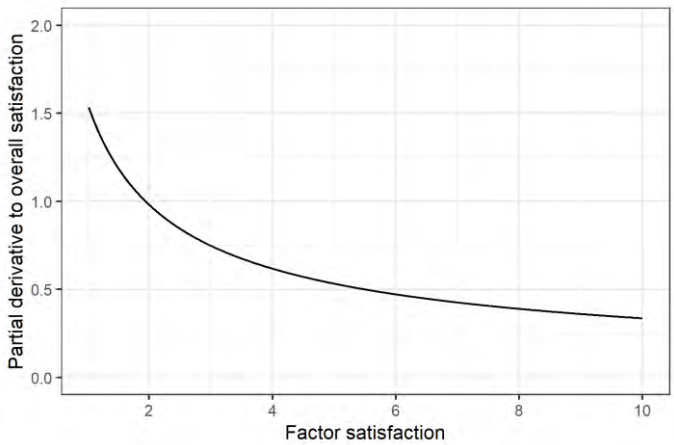

Figure 10 Correlation between factor satisfaction and partial derivative to overall satisfaction

The findings suggest a possible optimization principle of IEQ where improving the worst indoor environmental factor is the most effective way to improve overall satisfaction. The GM model also provides a general approach to evaluate satisfaction with overall environmental quality using satisfaction scores for individual environmental factors.

5 Limitations

A major limitation of the study is the number and types of subjects. Eight subjects, all of whom were graduate students majoring in Built Environment, participated in this study. Any 8 individuals cannot be considered to represent the general population. To the extent that the 8 participants were more or less sensitive to some factors of the environment, the results will be biased for the general population. It is also possible that the training received by the students could impact their perceptions and awareness of environmental parameters. A future study focusing on individual differences in sensitivity to IEQ would be helpful to address the generalization limitation.

In retrospect, it would have been better to select and vary an aspect of indoor air quality other than CO_2., as variations of CO_2 over the range used in this experiment did not impact IAQ satisfaction. An alternative indicator of IAQ such as odorous chemicals [59], VOCs from common source in office [60] , or ventilation rate would likely have been a better choice.

Another limitation is that each IEQ factor was represented by a single aspect. It is possible that variations of other aspects of one or more factors – e.g. color temperature or sound frequency – could have direct or subjective impacts different from the aspects varies in this study.

6 Conclusion

Experiments were carried out in which subjects were exposed to 31 prescribed sets of conditions in an IEQ laboratory. The comprehensive effect of individual indoor environmental factors was investigated. Two

questions have been answered:

1) For which factors of environmental quality is satisfaction subjectively impacted by aspects of other factors and what are the mathematical forms and magnitudes of these interactions?

- Satisfaction of thermal environment and visual environment were found to be influenced only by the directly related parameters of PMV and illuminance.
- Acoustic satisfaction was impacted mostly by sound pressure; illuminance was also found to have a slight impact which was more significant when sound pressure was low.
- CO_2 independent of the fixed, high ventilation rate was found to have no impact on perceived IAQ. The major factor affecting IAQ satisfaction was PMV; however sound pressure also had an impact.

2) How does satisfaction with individual factors influence satisfaction with the indoor environment overall? Do the factor satisfactions combine in a linear manner to predict overall satisfaction or in some other manner?

- The multicollinearity between the thermal satisfaction and IAQ satisfaction led to non-significant and biased estimations when predicting overall satisfaction with factor satisfactions.
- For the data obtained in this study, a geometric mean model had better prediction accuracy compared with a linear regression model and indicated a relative weighting scheme of factor satisfactions.
- This study found that the effect of an individual environmental factor on overall satisfaction changes with its level relative to other factors. In this study, an environmental factor had a greater impact on overall satisfaction when it had lower satisfaction compared with other factors.

7 Acknowledgments

This study was supported by the National Natural Science Foundation of China [Grant number 51978095]. Special thanks to all the subjects for their participation and cooperation during the experiments. Brett Singer contributed to the data interpretation and manuscript preparation, but not the study design; his

involvement was supported by the U.S. Dept. of Energy Building Technologies Office, Office of Energy Efficiency and Renewable Energy under DOE Contract No. DE-AC02-05CH11231.

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